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Biomass energy and the environmental impacts associated with its production and utilization

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ABSTRACT

Biomass is the first-ever fuel used by humankind and is also the fuel which was the mainstay of the global fuel economy till the middle of the 18th century. Then fossil fuels took over because fossil fuels were not only more abundant and denser in their energy content, but also generated less pollution when burnt, in comparison to biomass. In recent years there is a resurgence of interest in biomass energy because biomass is perceived as a carbon-neutral source of energy unlike net carbon-emitting fossil fuels of which copious use has led to global warming and ocean acidification.

The paper takes stock of the various sources of biomass and the possible ways in which it can be utilized for generating energy. It then examines the environmental impacts, including impact *vis a vis* greenhouse gas emissions, of different biomass energy generation–utilization options.

Contents

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1. Introduction

If solar energy is the 'mother' of all other forms of renewable energy, the primary source of food energy for all multi-cellular organisms is biomass.

Biomass is the general term which includes *phytomass* or plant biomass and *zoomass* or animal biomass. Sun's energy when intercepted by plants and converted by the process of photosynthesis into chemical energy, is 'fixed' or stored in the form of terrestrial and aquatic vegetation (Fig. 1). The vegetation when grazed (used as food) by animals gets converted into *zoomass* (animal biomass) and excreta. The excreta from terrestrial animals, especially dairy animals, can be used as a source of energy, while the excreta from aquatic animals gets dispersed as it is not possible to collect it and process it for energy production. In countries (for example China and India) where per capita energy consumption is low and the number of dairy animals large, even the excreta of dairy animals has the potential to provide a sizeable fraction of the total energy requirement [1,2]. But, in general, animal biomass contributes very little to the overall biomass potential of the world. Therefore, subsequent discussion shall focus on phytomass and, as is popular convention, the term biomass shall be used to denote only the phytomass.

The total incident solar energy reaching the earth's surface is enormous—173,000 TW (terawatt) [3], which is 17,000 times what the present day humans consume in fossil fuels. The upper limit of capture efficiency of solar radiation in biomass may be as high as 15% but in most of the species it is generally 1% or lower [4]. The energy thus captured by photosynthesis is about 140 TW which is a very small percentage of the total solar energy reaching our planet, yet the total volume of biomass that is created, is still very large—10 times our present energy demand. About 100 billion tonnes of carbon is converted to biomass every year.

These are attractive figures but, in practice, there are serious limitations on the extent to which biomass can be used as a source of generating other forms of energy. Moreover, much of the natural energy flow captured from sunlight is needed to run the hydrological cycle and earth's ecosystems. Humans cannot simply

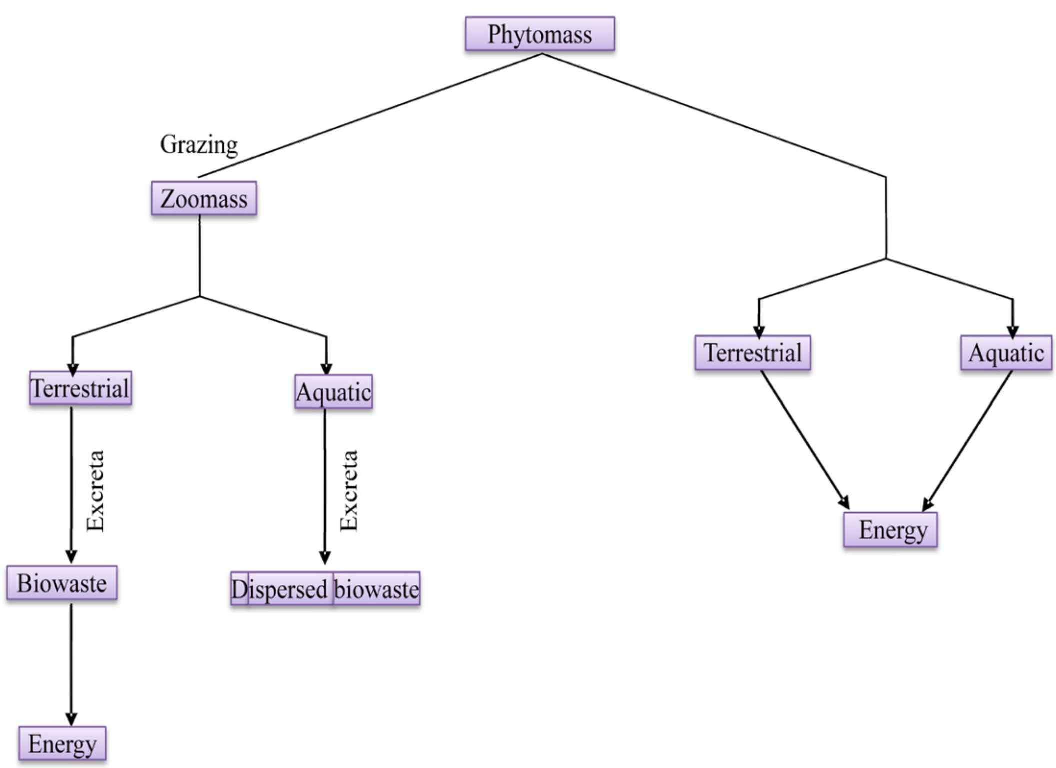

Fig. 1. The solar energy–biomass energy pathways.

divert excessive quantities of solar energy for use as fuel without causing serious disruptions in global environment [5].

Nevertheless, till large-scale use of fossil fuels started in the 19th century, for the previous hundreds of thousands of years human progress had been intimately linked to it's ability to utilize biomass as fuel and as food.

The very first form of energy (other than food) humankind learnt to use was biomass energy. And it remained its primary fuel right upto the end of 18th century. After discovering fire the next major discovery humankind made was of agriculture. In effect agriculture is our way to direct solar energy towards growth of only those plants, mainly (crops), that we deem 'useful' to us, at the exclusion of plants we do not want.

By facilitating the planting and growth of species of our choice while at the same time preventing other plants to grow on our agricultural lands, we have appropriated much of the terrestrial environment and created a situation to use solar energy via agriculture for our benefit.

There is historical evidence, based on cave drawings, that coal, a fossil fuel, was used for heating by the cave man and the existence of other fossil fuels has also been known since thousands of years [6]. But, until the 18th century when coal mining began and coal emerged as the dominant fuel of the industrial revolution, the human need for fuel was almost entirely met by biomass (in the form of wood and charcoal). Then fossil fuels—first coal and then petrol, diesel, and natural gas—began to dominate our fuel economy. Inspite of this, biomass in the form of fuelwood continues to be a major source of energy to this day, especially in developing countries. Nearly 70% of India's cooking energy requirement and 32% of its primary energy requirement is met with biomass [7]. Fuelwood and other forms of 'traditional biomass' contributes as much as 12.5% of Brazil's energy needs [8]. Globally fuelwood, in its various forms, accounts for about 64% the estimated total world supply of combustible renewables [9]. The estimated worldwide annual generation of electricity from biomass amounts to about 185 TWh, of which nearly three-quarters are produced from solid biomass, 14% from biogas and 12% from municipal solid waste. If we consider the portion contributed by biomass to the *total* energy production in the world, it comes to only less than 2% [10].

2. The logic of 'carbon neutral' nature of biomass energy

When we burn biomass, or use it after converting it to other types of solid, liquid, and gaseous fuels (for example charcoal, ethanol, methane), we release only that carbon to the atmosphere as CO_2 which the biomass had recently captured from atmosphere during its photosynthetic growth. So there is no *net* addition of CO_2. In contrast when we burn fossil fuels we make a net addition of CO_2 in atmosphere because fossil fuels are derived from plants and animals that had lived millions of years back. In that era the plants and animals had sequestered billions of tonnes of carbon over several thousand years. By burning large portions of that carbon per year we have released (and are continuing to release) enormous quantities of CO_2 within a very short time of about 200 years. The earth's environment cannot sequester this much carbon at the rate at which it is being released by fossil fuels. The result is the net enhancement of CO_2 concentration in the atmosphere, which, in turn, has led to global warming. The oceans have absorbed a third of all the extra CO_2 released in this period which has upset the CO_2-$CaCO_3$ balance of the oceans, causing a lowering in the ocean pH and setting in motion cascading negative impacts in several directions. If net CO_2 emissions are to continue, the acidification of the oceans will also continue, leading to consequences perhaps even more adverse than global warming alone is capable of causing [6,11]. For this reason fossil fuels have been deemed 'carbon positive'. Biomass, on the other hand, is 'carbon neutral'. Its use as fuel, directly or after conversion to other forms, is supposed to release only that much CO_2 which had been captured recently by the biomass for its growth.

This reasoning of 'carbon neutral' nature of biomass energy has generated renewed interest worldwide to utilize biomass, especially as a source of liquid fuels (methanol, ethanol, biodiesel, etc.) as substitutes for petrol and diesel. But, as discussed later in this chapter, biomass-based production of energy is not always 'carbon-neutral' because in actual practice fossil fuel-based energy is utilized at several points in the course of conversion of biomass into fuels. Even more significant is the fact, discussed in detail later, that large-scale production and utilization of biomass as energy source can be enormously harmful to the environment unless very great care is taken.

Nevertheless, the anxiety to quickly find alternatives to fossil fuels has prompted most countries of the world to explore biomass-based sources of energy.

3. Composition of biomass

Biomass contains varying amounts of cellulose, hemicellulose, lignin and small amounts of other organics besides inorganics. The relative proportion of the major organic components in biomass is particularly important in the development of processes for producing other fuels and chemicals.

The combination of cellulose, hemicelluloses, and lignin—all polymers—is called 'lignocellulose'. It comprises around half of the plant matter produced by photosynthesis and represents the most abundant renewable organic resource on earth. Cellulose, hemicellulose and lignin are strongly intermeshed in lignocelluloses and are chemically bonded by non-covalent forces or by covalent crosslinkages [12].

As of now only a small amount of lignocellulosic materials which is generated as by-products in agriculture or forestry is used, the rest goes to waste.

Cellulose is the largest component of lignocellulosic materials, followed by hemicellulose and lignin. Whereas cellulose and hemicellulose are macromolecules constructed from different sugars; lignin is an aromatic polymer synthesized from phenylpropaniod precursors. The composition and proportions of these compounds differ from plant to plant [14,15]; as illustrated in Table 1.

4. Sources of biomass for energy generation

Any and every type of biomass can be used to either burn it for energy or to derive one or other fuel from it. But some species provide better quality of fuel at lesser costs than other species. Energy-from-biomass programmes are built around such species.

4.1. Food crops

At present the following of the food crops are used in different countries to produce biofuels (ethanol, biodiesel, petrol/diesel additives):

i. Sugarcane
ii. Corn or maize
iii. Soyabean
iv. Wheat
v. Sugar beet
vi. Vegetable oils such as rapseed, palm, and sunflower oils.

Food crops-to-energy programmes are under increasing scrutiny because they compete with the use of these crops as food, thereby pushing up food prices and threatening the existence of subsisting human beings. They also seriously degrade land and

Table 1
Lignocellulosic constituents of some biomass.

Lignocellulosic residues	Hemicellulose (%)	Cellulose (%)	Lignin (%)	Ash (%)
Nut shells	25–30	25–30	30–40	NA
Corn cobs	35	45	15	1.36
Paper	0	85–99	0–15	1.1–3.9
Rice straw	24	32.1	18	NA
Sorted refuse	20	60	20	NA
Leaves	80–85	15–20	0	NA
Cotton seeds hairs	5–20	80–95	0	NA
Waste paper from chemical pulps	10–20	60–70	5–10	NA
Primary wastewater solids	NA	8–15	24–29	NA
Sugar cane bagasse	27–32	32–44	19–24	4.5–9
Wheat straw	26–32	29–35	16–21	NA
Barley straw	24–29	31–34	14–15	5–7
Oat straw	27–38	31–37	16–19	6–8
Rye straw	27–30	33–35	16–19	2–5
Bamboo	15–26	26–43	21–31	1.7–5
Coastal Bermuda grass	35.7	25	6.4	NA
Switch grass	31.4	45	12.0	NA
Rye grass (early leaf)	15.8	21.3	2.7	NA
Rye grass (seed setting)	25.7	26.7	7.3	NA
Orchard grass (medium maturity)	40	32	4.7	NA
Esparto grass	27–32	33–38	17–19	6–8
Sabai grass	23.9	NA	22.0	6.0
Elephant grass	24	22	23.9	6
Bast fiber seed flax	25	47	23	5
Bast fiber Kenaf	22–23	31–39	15–19	2–5
Bast fiber Jute	18–21	45–53	21–26	0.5–2
Banana waste	14.8	13.2	14	11.4
Hardwood stems	24–40	40–55	18–25	NA
Softwood stems	25–35	45–50	25–35	NA

water bodies. These aspects have been discussed in detail later in this paper.

4.2. Hydrocarbon-rich plants

A large number of pants contain hydrocarbons in concentrations significant enough to become a potential source of a diesel-like fuel. In just the north-eastern region of India, 99 species of such 'laticiferous' (latex-yielding) species have been identified [13]. Well-known among hydrocarbon-rich plants are jatropha (seven species), and euphorbia (five species) but the potential of several others (Table 2) has also been indicated. In these plants the organics are generally concentrated in stem and bark; leaves carry much lower fractions of these (Table 3).

Even as great hope is pinned by some on these plants, the negative impact of their large-scale use is similar to that of food crops, as discussed later.

4.3. Waste

'Waste' includes agricultural residues such as straw, vegetable/fruit peels, and crop wastes; forestry waste such as leaf litter and sawmill waste; food waste; and biomass components of municipal solid waste. Substantial energy can be produced from these wastes because, globally, several billion tonnes of biomass is contained in them. But to actually extract the energy in a clean and cost-effective manner is a major challenge yet to be met. Among the biggest problems is how to quickly and economically convert the lignocellulosic component of these wastes into simpler sugars to enable their subsequent biochemical conversion to clean fuels like ethanol and butanol. This aspect is dwelt upon at some length in Section 5.2.

In India alone over 500 million tonnes of agricultural and agro-industrial residue is generated every year. This quantity, in terms of heat content, is equivalent to about 175 million tonnes of oil. A portion of agricultural residue is used for fodder and fuel in rural areas but at least 150–200 million tonnes of it goes to waste. Theoretically there is enough energy content in the waste to generate 15,000–25,000 MW of electrical power in India at typically prevalent plant load factors [7]. Electricity can also be generated from biomass growing on wastelands, road side and rail trackside plantations, etc. The quantum of electricity that can be produced from such biomass has been estimated to be in excess of 70,000 MW. Thus, the total electricity generation

Table 2
Some key constituents and fuel values of latex-bearing plants [13].

Species	Oil (%)	Polyphenol %	Hydrogen (%)	Fat (%)	Protein (%)	Gross heat in hexane extract
Plumeria alba	3.56	7.89	1.36	26.8	7.87	8325
Calotropis procera	3.07	8.42	2.04	24.3	11.26	9837
Ficus carica	1.21	4.26	0.94	21.2	8.21	–
Erythrina variegate	1.01	5.26	0.29	27.4	7.62	–
Euphorbia nerrifolia	3.87	12.49	3.28	30.6	12.68	9218
Allamanda catherlica	1.38	7.24	1.26	21.82	8.16	
Neriumindicum	3.01	8.25	1.48	24.4	10.21	7145
Tabernaemontana divarieta	1.36	7.42	0.86	32.5	9.26	–
Mimusops elengi	5.37	10.26	3.12	24.7	11.23	8924
Euphorbia pulcherima	3.94	8.42	2.41	28.3	9.42	–
Crude oil	–	–	–	–	–	10506
Gasoline	–	–	–	–	–	11528

Table 3
Distribution of organics in some hydrocarbon-rich species [13].

Species	Plant parts	Moisture content (%)	Oil (%)	Polyphenol (%)	Hydrocarbon (%)
Plumeria alba	Leaf	87.5	0.21	3.86	0.26
	Stem	56.8	3.36	6.84	1.28
	Bark	89.3	4.74	7.62	1.78
	Whole plant	76.3	3.56	6.89	1.36
Calotropis procera	Leaf	69.1	1.68	2.58	1.06
	Stem	64.6	3.64	3.56	2.47
	Bark	76.9	3.89	3.96	2.6
	Whole plant	71.5	3.11	3.42	2.35
Euphorbia nerrifolia	Leaf	73.8	2.46	4.67	0.42
	Stem	62.4	3.56	9.63	2.58
	Bark	86.9	4.95	12.68	2.93
	Whole plant	78.6	3.87	11.49	2.28
Nerium indicum	Leaf	64.3	2.1	4.21	0.34
	Stem	62.4	3.71	6.23	1.36
	Bark	70.9	3.24	8.25	1.78
	Whole plant	67.2	3.24	7.54	1.45
Mimusops elengi	Leaf	65.2	1.36	1.46	1.21
	Stem	57	6.54	8.43	3.56
	Bark	61.4	8.21	8.91	3.92
	Whole plant	59.3	6.87	7.69	2.42

potential from biomass could reach a figure of about 100 GW in India alone [7] if the technological problems in the way of doing it can be solved.

4.4. Weeds and wild growths

Invasive plants which outgrow their utility to humans are called weeds. The terrestrials mimosa and lantana, the amphibian ipomea, and the aquatics water hyacinth, salvinia, and pistia are examples of weeds [16–22]. Invasive plants elbow out most other species and have a destabilizing and degrading effect on the areas they colonize. If such plants can be utilized as energy source it would become economically feasible to periodically harvest and use them, thereby controlling their spread and reducing the harm they cause [23].

4.5. 'Lignocellulosic' biomass: fast-growing grasses and woody species

As stated in the beginning of this section a large number of biomass species contain lignocelluclose but the term 'lignocellulosic biomass' is being commonly used in reference to species which are being targeted for energy production principally for their lignocellulosic content and do not compete with food crops.

Lignocellulose being the main component of biomass, gigantic quantities of it is generated across the globe. Agricultural residues—presently deemed waste—contain massive quantities of lignocellulose (Table 4). Lignocellulosic biomass also contains trace amounts of several inorganics which get concentrated in the ash (Table 5).

Unlike some bioenergy crops like corn and soybeans, which are annuals, lignocellulosic bioenergy crops are typically perennials. They include:

(a) Woody species such as willows, *Salix* spp. [24], poplars, *Populus* spp. [25], and other hardwoods [26].
(b) Herbaceous species such as switchgrass, *Panicum virgatum* [27]; big blustem, *Andropogon gerardii* [28]; reed canarygrass, *Phalaris arundinacea* [29]; and miscanthus, *Miscanthus* spp. [30].

Of these, switchgrass has received particular attention due to its high biomass yield, broad geographic range, efficient nutrient utilization, low erosion potential, carbon sequestration capability, and reduced fossil fuel input requirements relative to annual crops [31]. Poplars and miscanthus are also being intensively explored.

Even as production of 'lignocellulosic biomass' like switchgrass is less stressful to environment than food-based crops, it is not without potential pitfalls. Care must be taken when selecting species for use as biofuel crops, because the characteristics which make some species ideal for this use, such as C4 photosynthesis, long canopy duration, lack of pests and diseases, and rapid spring growth, are the ones also associated with invasiveness [32]. Many lignocellolosic crops can be grown with low agrochemical and fossil fuel inputs, but lure of quick profit can make farmers overuse this ability by employing intensive cropping practices with high or even excessive fertilizer and pesticide inputs [33]. If such misuse occurs, the advantage of carbon sequestration by switchgrass stands developed with high levels of nitrogen fertilization many release N_2O into the atmosphere and significantly offset the greenhouse gas mitigation potential of such stands [34]. Lignocellulosic crop production can also have a large impact on wildlife habitat and biodiversity [35].

Table 4
Lignocellulosic residues generated from different agricultural sources.

Source	Residue, million tonnes per year	Volatile matter (%)	Ash (%)
Sugarcane bagasse	317–380	84.2	2.9
Maize straw	159–191	–	–
Rice husk	157–188	81.6	3.5
Wheat straw	154–185	83.9	11.2
Soya straw	54–65	–	–
Yucca straw	40–48	–	–
Barley straw	35–42	–	–
Cotton fiber	17–20	88	5.4
Sorgoum straw	15–18	–	–
Banana straw	13–15	–	–
Mani shell	9.2–11.1	–	–
Sunflower straw	7.5–9.0	–	–
Bean straw	4.9–5.9	–	–
Rye straw	4.3–5.2	–	–
Pine waste	3.8–4.6	–	–
Coffe straw	1.6–1.9	–	–
Almond straw	0.4–0.49	–	–
Hazelnut husk	0.2–0.24	–	–

Table 5
Inorganics in biomass ash, ppmw (mg kg^{-1}).

Substance	Na	K	Ca	Al	Fe	Mg	P	Si	Co	Cr	Cu	Mn	Ni	S	Zn
Bagasse	93	2682	1518	[a]	125	6261	284	17340	[a]	[a]	18	9	16	60	16
Coconut coir	1758	2438	477	148	187	532	47	2990	0.6	2	68	4	2	64	25
Coconut shell	1243	1965	1501	73	115	389	94	256	0.5	0.3	5	1	13	35	9
Coir pith	10564	26283	3126	1653	837	8095	1170	13050	3.2	0.2	1239	27	22	476	40
Corn cob	141	9366	182	[a]	24	1693	445	9857	[a]	[a]	[a]	19	6	15	11
Corn stalks	6463	32	4686	1911	518	5924	2127	13400	8	11	32	12	13	564	32
Cotton	1298	7094	3737	[a]	746	4924	736	13000	[a]	[a]	[a]	38	10	58	22
Groundnut shell	467	17690	12970	3642	1092	3547	278	10960	2.3	6	11	44	11	299	52
Millet husk	1427	3860	6255	[a]	1020	11140	1267	150840	[a]	[a]	[a]	38	49	317	94
Rice husk	132	9061	1793	[a]	533	1612	337	220690	[a]	[a]	21	108	32	163	1244
Rice straw	5106	5402	4772	[a]	205	6283	752	174510	[a]	[a]	[a]	463	45	221	47
Subabul	92	614	6025	[a]	614	1170	100	195	[a]	[a]	1	2	1	66	40
Wheat straw	7861	28930	7666	2455	132	4329	214	44440	[a]	[a]	7	25	25	787	18

[a] Below detectable levels.

5. Technical routes for obtaining different types of fuels from biomass

Biomass can be, and is, directly used as fuel but this manner of use is a source of very substantial pollution [36,37]. Also biomass cannot be used as it is to run vehicles, trains, ships, and airplanes. It is therefore, necessary to convert biomass into liquid fuels which can replace petrol and diesel. For other uses as fuel, biomass should be converted to gases like methane which burn much more cleanly than biomass.

A large variety of liquid and gaseous fuels can be derived from biomass (Fig. 2). These are all carbon-containing fuels which, on burning, generate mainly carbon dioxide and water vapour. Biomass can also be used to generate the non-carbon fuel hydrogen (Fig. 3) but all existing technologies which do so are too costly to be practicable. As may be seen from Fig. 3, there are two main routes available for producing fuels from biomass: thermochemical and biochemical.

5.1. Thermochemical convertion of biomass

In thermochemical processing biomass is converted into a range of products by thermal decay and chemical reformation. It essentially involves heating biomass in the presence of differing concentrations of oxygen.

When biomass is heated in total absence of oxygen, the process – called pyrolysis – produces various organic liquids that can be manipulated or refined to make liquid fuels. Alternatively, heating with low concentrations of oxygen leads to gasification and the production of hydrogen and organic gases which, in turn, can also be converted into liquid fuels by the Fisher-Tropsch process. The advantage of thermochemical processing is that it can convert nearly all the organic components of the biomass, whereas biochemical processing (described below), uses only the polysaccharide content of the biomass. But the start-up and plant maintenance costs of thermochemical processes are high because of the demands of high-temperature processing. In order to operate efficiently, thermochemical processing must be done on a large scale which necessitates the transportation of biomass over long distances, resulting in an increase in cost. Also, thermochemical processes use up a lot of fossil fuels in the course of transportation of biomass and its heating. Therefore such processes provide little benefit *vis a vis net* reduction of CO_2 emissions. Additionally, such processes generate substantial quantities of air pollutants, necessitating elaborate treatment which is a major drain on energy and other resources. There is also a risk of major accidents [38–44].

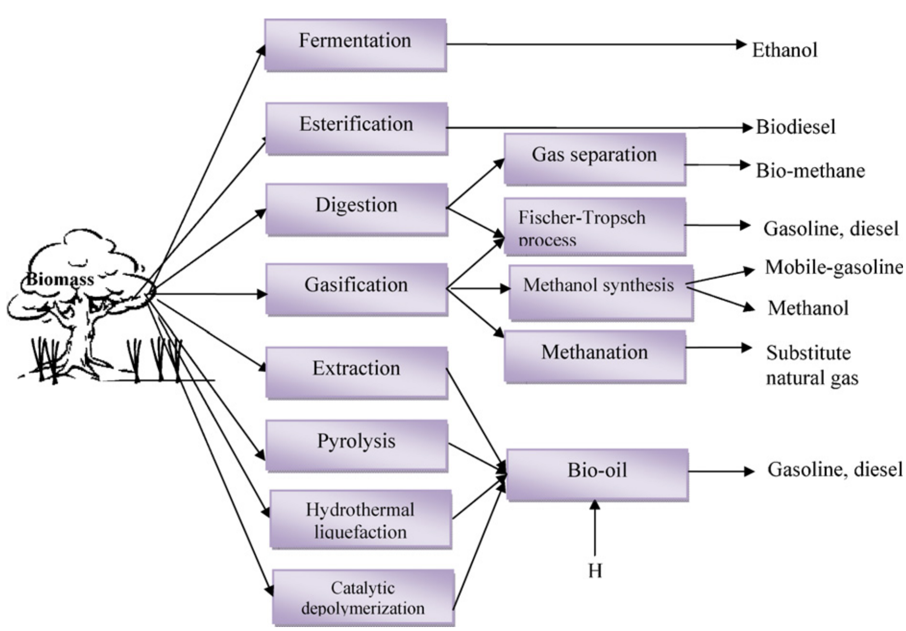

Fig. 2. Different types of fuels obtainable from biomass [170].

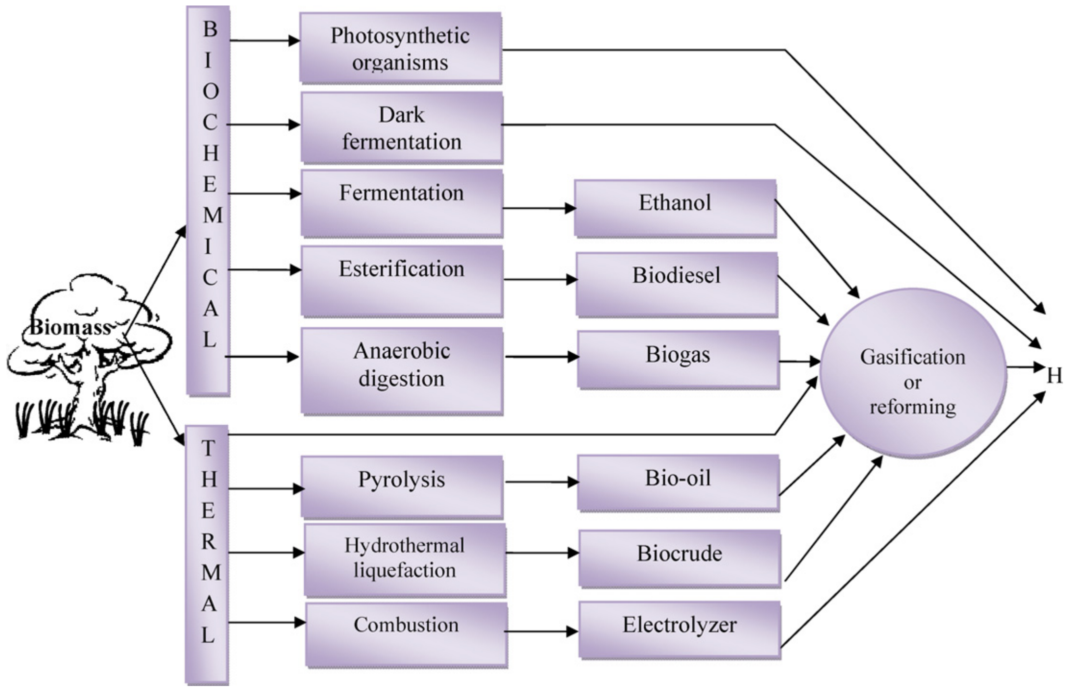

Fig. 3. Routes by which hydrogen can be produced from biomass [170].

5.1.1. Cogeneration or 'combined heat and power (CHP)' generation

'Cogeneration' or CHP denotes the process which uses a single fuel to produce more than one form of energy, in sequence. It is possible to cogenerate steam and electricity, thereby significantly increasing the overall efficiencies of fuel utilization in process industries. The thermodynamics of electricity production necessitates the rejection of a large quantity of heat to a lower temperature sink. In normal electricity generation plants, this heat rejection takes place in condensers where up to 70% of heat in steam is rejected to the atmosphere. In cogeneration mode, however, this heat is not wasted and is instead used to meet process heating requirement. The overall efficiency of fuel utilization can thus be increased to 60% or even higher in some cases. Capacity of cogeneration projects can range from a few kilowatts to several megawatts of electricity generation along with simultaneous production of heat ranging from less than a hundred kWth (kilowatts thermal) to many MWth (megawatts thermal).

Cogeneration requires heat and electricity in a favourable ratio, which is ideally present in the sugar industry. For this reason sugar industry across the world has been using bagasse-based cogeneration for achieving economy of operations. In India, almost all sugar mills have been practicing cogeneration; some since 70–80 years. Technology is now available for high-temperature/high-pressure steam generation using bagasse as a fuel. This makes it possible for sugar mills to operate at higher levels of energy efficiency and generate surplus electricity. CHP systems generally offer higher carbon savings than power only systems, but have less favourable economics mainly due to high initial capital costs [37].

5.1.2. Electricity from biomass-fired power plants

Biomass-fired power plants have been explored, especially in developing countries. For example in India power-generation capacity of about 302 MW has been commissioned through 54 projects by India's Ministry of New and Renewable Energy Sources [7]. A further capacity addition of about 270 MW through 39 projects is under implementation. The biomass materials that have been used for power generation in these projects include rice husk, cotton stalk, mustard stalk, *Prosopis juliflora (vilayati babul)*, poultry litter, bagasse, cane trash, etc. State-wise distribution of the commissioned and 'under implementation' plants in India and their capacity is given in Table 6. Among developing countries Brazil is the greatest producer of electricity from biomass-fired power plants [8]. In recent years developed countries are also increasing their capacities and numbers of such systems [45].

5.1.3. Use of biomass gasifiers

Biomass gasifiers can be used to replace fossil-fuels in high fuel-consuming industries such as the ceramics industry. The production of ceramics requires that raw items be baked for a pre-specified period at a temperature of 900–1300 °C. This is carried out in tunnel kilns, which operate continuously round the year. Oil or other suitable fuels are fired into the kilns to maintain the high temperature. Typically, kerosene, diesel or LPG are used as fuels. These can be replaced by producer gas generated in biomass gasification systems. The typical oil consumption of ceramic factories is 2000–3000 l/day. After installation of biomass gasifiers, oil consumption could be reduced to less than a third. It is estimated that the Indian ceramic industry consumes 0.3–0.5

Table 6
State-wise list of commissioned and 'under implementation' biomass based projects [7].

State	Commissioned projects		Projects under implementation	
	Number of projects	(MW)	Number of projects	(MW)
Andhra Pradesh	37	194.2	11	70.25
Chhattisgarh	2	11	5	51
Gujarat	1	0.5	–	–
Haryana	1	4	–	–
Karnataka	5	36	11	61
Madhya Pradesh	1	1	–	–
Maharashtra	1	3.5	1	6
Punjab	1	10	1	6
Rajasthan	1	7.8	4	29.1
Tamil Nadu	4	34.5	6	48.5
Uttar Pradesh	–	–	–	–
Total	54	302.5	39	271.85

million tonnes of oil per year. Seventy per cent savings on this figure would imply annual savings of 0.02–0.35 million tonnes of oil. According to MNRE [7], about 100 ceramic factories in India out of the estimated 500 are reported to have switched over to biomass gasifiers. But it is necessary to assess the pollutant emissions and other impacts from gasifiers in comparison to the emissions from fossil fuel use before recommending the former.

5.2. Biochemical processing

Of the five alternatives available for biochemical processing of biomass (Fig. 3) the first two are only in experimental state. Of the remaining three, anaerobic digestion, which has been used with increasing success in processing animal manure and wastewaters [46] has been besieged with operational problems and low efficiency when used to process phytomass [23,47]. In the esterification-to-biodiesel route the main challenge is to grow oil-rich plants in sufficiently large quantities per acre of land to maximize oil yield with minimum of environmental costs. In the fermentation-to-ethanol route, also, this is a major concern but equally big concern is the conversion process which, as per mounting evidence, is far from 'clean'. Indeed, as detailed in the later part of this paper, some scientists even claim that the overall process is so polluting, and consumes so much energy, that in the ultimate analysis it generates more greenhouse gas emissions than the gasoline it replaces as a transportation fuel. In the context of this view-point as well as of the popular belief that biofuels are 'clean', the process of ethanol production is discussed in more detail below.

A broad overview of the route by which food crops other than cane sugar are converted to ethanol is presented in Fig. 4. The system in greater detail is shown in Fig. 5. In the food crops the sugars are in the form of starch which has to be first converted to simpler sugars – maltose, glucose, fructose – before fermentation to ethanol can be accomplished. For this the substrate has to be pulverized and then cooked in steam to cause gelatinization and then rupture of starch granules. Cooling and addition of fungal amylase leads to hydrolysis into simpler sugars. In the next, fermentation, stage these sugars are converted by yeasts into ethanol.

Only when sugarcane juice is the raw material for ethanol production, the cooking and hydrolysis stages are not required.

As the fermentation is done in presence of water the resulting ethanol is in a dilute form. To be usable as a fuel, ethanol must be freed of water. Most of the water is removed by distillation, but only upto 95–96% concentration of ethanol can be achieved due to the formation of water–ethanol azeotrope. The 95.6% (m/m) (96.5%, v/v) ethanol, 4.4% (m/m) (3.5%, v/v) water mixture may be used as a fuel alone, but unlike anhydrous ethanol, it is immiscible in gasoline, so the water fraction has to be removed in further treatment in order to produce ethanol pure enough to burn in combination with gasoline in gasoline engines.

Five processes are available to remove water from an azeotropic ethanol/water mixture. The first process, used in many early fuel ethanol plants, is called azeotropic distillation and consists of adding benzene or cyclohexane to the mixture. When these components are added to the mixture, it forms a heterogeneous azeotropic mixture in vapour–liquid–liquid equilibrium, which when distilled produces anhydrous ethanol in the column bottom, and a vapour mixture of water and cyclohexane/benzene. When condensed, this becomes a two-phase liquid mixture. Another early method, extractive distillation, consists of adding a ternary component which increases ethanol's relative volatility. When the

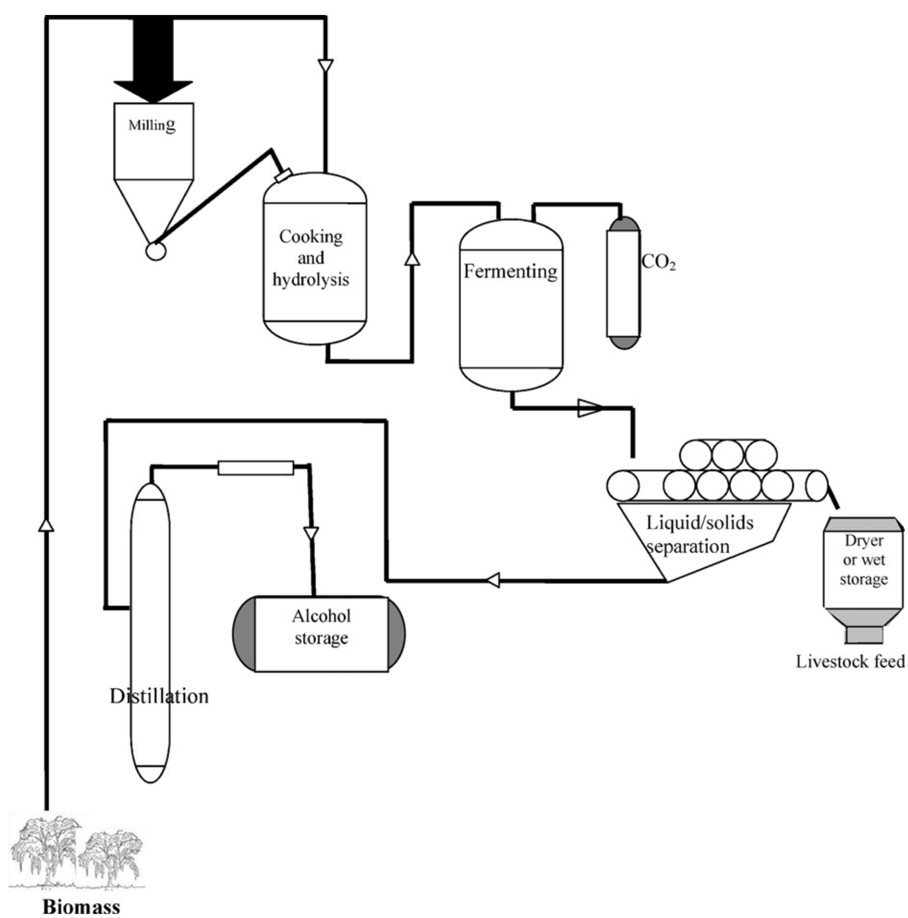

Fig. 4. A broad overview of the biomass-to-ethanol process using food crops (corn, maize, wheat, etc.) Adapted from [171].

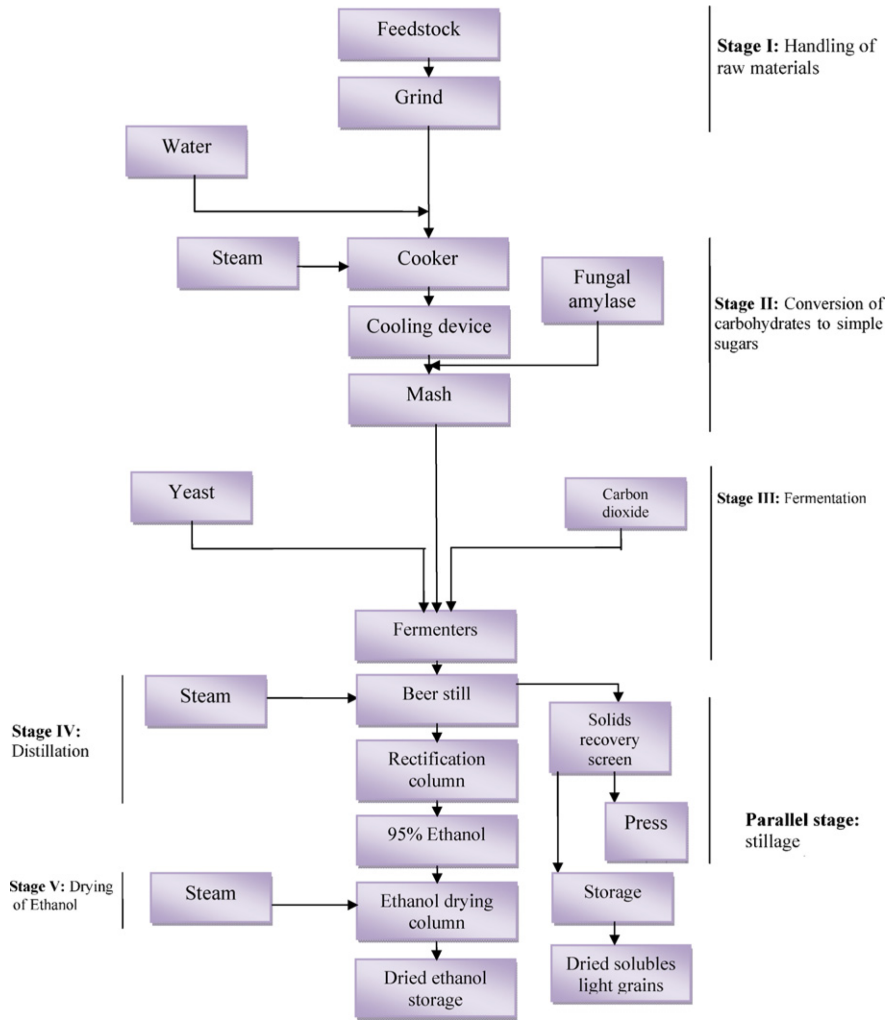

Fig. 5. Stages associated with the production of ethanol from starch contant of food crops Adapted from [172].

ternary mixture is distilled, it produces anhydrous ethanol on the top stream of the column.

All these processes consume substantial quantities of energy. Attempts have, therefore, been made to develop methods that avoid distillation for achieving dehydration. One of such processes uses molecular sieves to remove water from ethanol. In this process, ethanol vapour under pressure passes through a bed of molecular sieve beads. The bead's pores are sized to allow absorption of water while excluding ethanol. After a period of time, the bed is regenerated under vacuum to remove the absorbed water. Two beds are used so that one is available to absorb water while the other is being regenerated. This dehydration technology is less energy intensive than azeotropic distillation.

As can be easily seen, substantial quantities of fossil fuel energy is consumed in the ethanol production process. From raising the crop to harvesting, transporting, milling, and cooking, fossil fuels are continuously used-up. Considerable energy is also consumed in the dehydration of ethanol. The ultimate product, in the opinion of many, might consume more energy than it may provide.

5.2.1. Production of ethanol from lignocellulosic crop

With growing opposition to the diversion of food crops for biofuel production, and growing acceptance of the fact (as detailed later in this paper) that it is not as clean and green a process as has been projected in the past, focus is shifting towards 'lignocellulosic' biomass. Whereas the starch-rich seeds of corn or maize constitute but a small fraction of the biomass of the overall plant, all other parts of plants are full of lignocellulose. Hence for every acre of land committed to biomass-for-energy, much greater quantities of lignocellulosic biomass can be produced than a food crop. But lignocellulose is not as easily hydrolysable to simple sugars as starch. It has to be pre-treated by much more 'strong arm' methods than are used for starch before sugars can be extracted from it. The reason is as follows.

Plant cell walls are very sturdy fibre-composite materials that make for much of the characteristic form and function of plants. Young growing plant cells are encased in a strong but flexible cell wall, allowing cells and organs to expand as the plant grows. In older tissues, the cell walls become substantially rigidified and are reinforced by the deposition of secondary cell walls. It is these secondary cell walls that provide mature plant tissues with their strength and resilience, forming the woody tissues which, for example, allow trees to attain their great sizes, and the stems of crops such as wheat to bear the weight of seeds produced on the plant. The major portion of plant cell walls is composed of polysaccharides and hence is potentially a rich source of sugars for fermentation to produce biofuels.

The problem is that plant cell walls have evolved not only for strength but also for resistance to biochemical attack by living organisms. The cell wall is the first barrier between plant cells and the environment. Pests and pathogens try to penetrate the cell wall while the plants build their defenses by strengthening the cell wall. Even senesced woody tissues must resist pests to enable the tissues to perform their skeletal support function.

Thus, plant cell walls have evolved as materials that are extremely resistant to enzymatic digestion. Obtaining sugars that are locked in this structure is a major challenge. Among the existing routes to penetrate the plant cell walls is the acid hydrolysis method, which uses acids such as sulphuric acid or hydrochloric acid. It involves costly, energy-demanding steps to recover the acid used, and to condition the released sugars for fermentation.

The other option is enzymatic process, which uses enzyme mixtures to obtain fermentable sugars from biomass. But pretreatment is needed to allow the hydrolytic enzymes to access their substrates. Several physical, chemical and enzymatic pretreatments have been developed to improve the digestibility of biomass, but the need to reduce the energy inputs, and the costs of the procedure in general, has generated consensus around the use of simple thermochemical pretreatments. Pretreatments with ammonia improves digestibility by decreasing the crystallinity of cellulose fibrils or, at high temperatures, by depolymerizing lignins and releasing matrix polysaccharides [48].

One of the most cost-effective pretreatments is the use of dilute acids (usually between 0.5 and 3% sulphuric acid) at moderate temperatures [49]. This enables the removal of hemicellulose and the recovery of the component sugars. While lignins are not removed by this treatment, their disruption results in a significant increase in sugar yields. The efficiency of hydrolysis is increased by acid pretreatment, but this also raises the costs because of the need for costly equipment and post-treatment neutralization.

Following enzyme treatment, the sugars released need to be recovered and conditioned into a form suitable for fermentation into the appropriate alcohol. Serious difficulties are encountered in this step also because several byproducts of the cellulose pretreatment (for example acetate, furfurals, furans, and aromatics) have the potential to inhibit microbial growth during the next, i.e., the fermentation stage. The end product sought is generally ethanol, although there has also been renewed interest in the production of butanol in recent years [50]. The potential advantages of butanol over ethanol as a transportation fuel are that butanol is less hygroscopic than ethanol, can be mixed at higher levels with gasoline for uses in conventional engines, and has a higher energy density in comparison with ethanol [51].

A comparative chart which clearly brings out the increasing complexity of ethanol production process as we move from cane sugar as raw material to lignocellulosic biomass, is presented as Fig. 6.

5.3. Emerging technologies

New technologies for producing biofuels from biomass are rapidly emerging, including the development of engineered yeast for increased ethanol yields [52], utilization of new microorganisms for ethanol production [53], pretreatments for cellulosic digestion [54], fuel cells for converting sugars directly to electricity [55], and catalysts for more efficient conversion of biomass to syngas [56].

Use of lignin degrading fungi is being explored and attempts are being made to isolate—and if possible genetically modify—lignin-degrading microorganisms living in the gut of higher termites [57]. A new biodiesel product, called microdiesel, can be generated in engineered bacterial cells that condense ethanol with fatty acids [58]. But these efforts are all in exploratory state with nothing having come close to actual utilization.

Considerable R&D is also being done on microalgae which are regarded as more photosynthetically efficient than terrestrial pants and as a consequence are more efficient CO_2 fixers [59]. This ability of algae to fix CO_2 has been proposed as a method of removing CO_2 from flue gases from power pants, thereby reducing the GHG emissions. Many algae are rich in oil, which can be converted to biodiesel. The oil content of some microalgae exceeds 80% of dry weight of the algal biomass [60,61].

The net annual harvest of algal biomass cultivated in subtropical areas can be as high as 40 tons ha^{-1} (dry matter), even higher if CO_2 is supplied. It is possible to produce about 100 g m^{-2} d^{-1} of algal dry matter in simple cultivation systems [62,63]. It has been calculated that acre to acre algae could produce almost 100 times more oil than soybean [64]. Most importantly algae can be grown either in fresh-waters or marine waters thereby avoiding the use of land.

Approximately half of the dry weight of microalgal biomass is carbon (Miron et al., 2003), which is typically derived from CO_2.

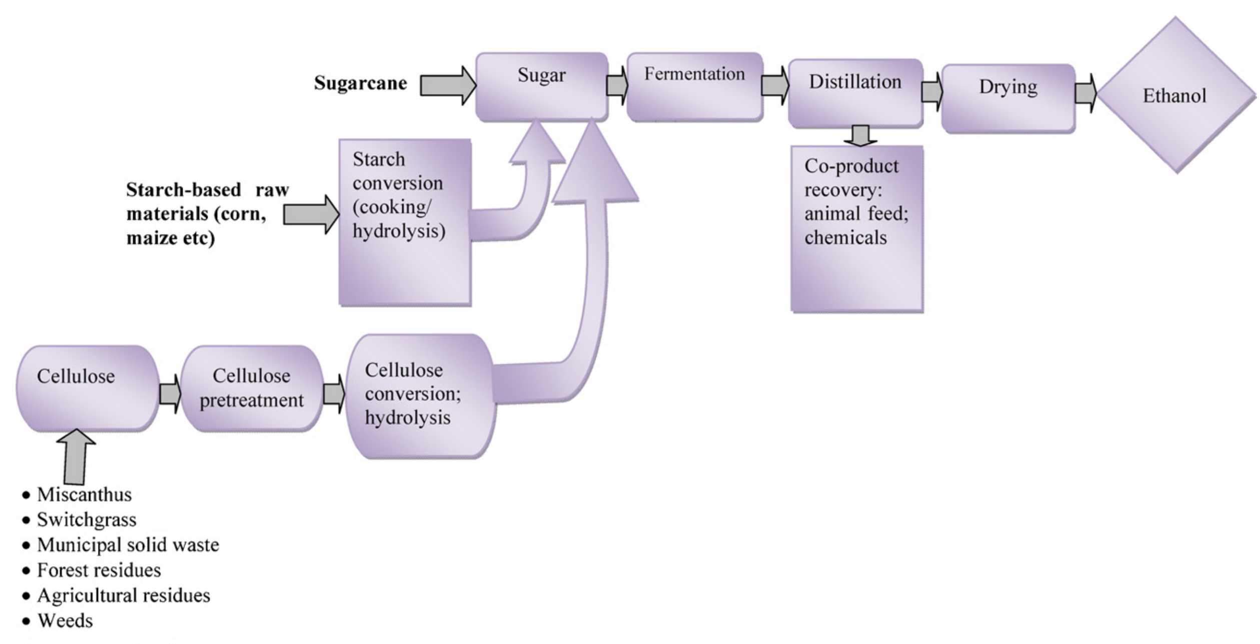

Fig. 6. Increasing number of pre-treatment steps associated with the production of ethanol from increasingly complex sugars; whereas sugarcane juice can be directly fermented, starch containing food crops and lignocellulosic biomass need increasingly more challenging pretreatment Adapted from [173].

Table 7
Leading options for biomass energy*.

Biomass-energy option	Problems	Advantages
Food to ethanol (C_2H_5OH)	Very low net energy yield; competition with food crops; air and water pollution; low yield per unit area	Popularly perceived to be a 'green' and 'clean' option, which in reality it isn't
Food crop to butanol (C_4H_9OH)	Net energy yield still quite low even if better than ethanol; competition with food crops; air and water pollution; low yield per unit area	Better net energy yield than ethanol
Lignocellulosic biomass to ethanol or butanol	Unproven at a large scale; low net energy yield; positive attributes may lead to over exploitation and consequent harm to the environment	Higher yield per unit area; cultivable on degraded lands; less severe competition with food crops,; less natural resource degrading then food crops
Zoomass (animal waste) to methane (CH_4)	Conversion efficiency is not yet high enough; presently the unit cost is higher than from natural-gas deposits	Proven technology; can use residues and wastes, turns potential pollutant into an energy resource; CH_4 capture infrastructure is in place
Zoomass to hydrogen (H_2)	Conversion efficiency is very low; far from feasible as of present	Can use residues and wastes; effects pollution control; H_2 can be used in fuel cells
Zoomass to electricity via the microbial fuel cell (MFC)	Technology is nascent; conversion efficiency is not established	Electricity infrastructure is in place; an MFC is a combustionless, pollution free fuel-cell technology that uses renewable organic fuel directly
Hydrocarbon-rich plants to biodiesel	Yield per unit area unproven; competes with food crops; lure of quick benefit may cause diversion of fertile lands to their cultivation	Biodiesel is a high-density fuel that is as efficient as, but less polluting, than petroleum
Phototrophic microorganisms (algae or cyanobacteria) to biodiesel	Technology is at an early stage; may require significant capital investment	Biodiesel is as efficient as but cleaner than petroleum; possible to have very high yield per unit area, does not compete with food crops

* Adapted from Karp and Shield [169].

Thus, producing 1 kg of algal biomass fixes 1.6–1.8 kg of CO_2. Notwithstanding all the above-mentioned attractive prospects and calculations, the use of algae for biofuel production is prohibitively costly and is not being attempted commercially at all. We can only hope that breakthroughs in R&D will change this situation for the better.

All the biomass energy options with their pros and cons in perspective, are summarized in Table 7.

6. Future outlook

Even as USA, Brazil and several other countries are continuing to use food crops like corn (maize), sugarcane, and soyabean for generating biofuels [8,9,65,66], it is unlikely that this approach will be sustainable for long. In the subsequent parts of this paper we have dealt elaborately on the technical, environmental and societal problems associated with the use of food crops as an energy source. Likewise there are serious environmental costs associated with large-scale use of hydrocarbon-rich plants like euphorbia and jatropha.

Extensive research is underway [67] to develop processes with which biomass can be fermented to hydrogen ('dark' anaerobic digestion) and several other avenues are being explored as detailed in the preceding section. But none of the options is anywhere near economic feasibility.

At present great hope is pinned on high-yielding lignocellulosic biomass like switchgrass, which can be grown on degraded lands, as a source of raw material for ethanol and other biofuels [65,68,69]. But while the technology for conversion of food crops (corn, sugarcane, soyabean, etc.) to ethanol is well established, the conversion of lignocellulosic biomass to ethanol has still to overcome challenges such as cost of pretreatment methods, cost of hydrolytic enzymes and inefficient fermentation of pentoses. Among the suggestions to improve the economics of bioethanol production from switchgrass is by developing value-added by-products such as proteins [70]. There is need for better processes which can efficiently utilize hemicellulose, as it accounts for about 20–25% of switchgrass. It is being hoped that with the development of genetically engineered microorganisms capable of efficient pentose fermentation, ethanol production from hemicelluloses in switchgrass can be made more cost-effective [71].

Going by hindsight, even as improvements in genetics, agronomy and the conversion process may help in the development of economically feasible biofuel production systems from switchgrass and other lignocellulosic biomass, the environmental and social stresses associated with dedicating large geographic areas for growing such species would remain major concerns, given the increasing requirement of land for producing food for the increasing global population.

7. Environmental impacts of biomass energy: centralized (large scale) systems

7.1. The proposed large scale systems

Several basic system-types have been propounded.

7.1.1. Hydrocarbon-rich-arid-land plants

Efforts to cultivate hydrocarbon-producing plants for fuel production had been made by the Italians in Ethiopia [72] and the French in Morocco [73] but it was the initiative of the Nobel Laureate (in chemistry) Melvin Calvin which caused great public attention towards the possible use of hydrocarbon-rich plants as a source of petrol-like fuel [74,75]. It was an interesting prospect and appeared particularly charming when articulated by a Nobel Laureate. It evoked great interest and was celebrated in various forms, including imaginative illustrations which showed petrol-meters nailed to the trees, and the type of dispenser we see at petrol pumps hanging by its side. The artist's intention being to portray trees as 'petrol pumps of the future'. Some other illustrations depicted trees in the form of cows from where liquid fuel was being 'milked'.

With the passage of time it was realized that not one or two trees but hundreds of trees, covering several acres of land, would be required to generate sufficient liquid fuel to run a single petrol pump. Among the most promising of hydrocarbon-rich plants–*Euphorbia lathyris*–could at best yield energy equivalent of 25

barrels (about 5000 litres) of petroleum per hectare! Much less than what an average petrol pump dispenses in a few hours! Johnson and Hinman [76] estimated that it would require as much as 12 million hectares (46,000 square miles) of *E. lathyris* plantations to generate enough oil to meet a mere 10% of the petroleum demand of the USA. The stress such a massive plantation would have caused on soil moisture—through uptake as well as evapotranspiration of precious water—was not estimated but would obviously have been quite great. There would have been other impacts of a large magnitude—on soil productivity, microclimate, and wildlife—some of which would have been disastrous to the ecology of the region.

So, Calvin's idea was not given a serious trial as its shortcomings became more and more obvious with every step taken in the direction of assessing its feasibility. Very wide variations in the yield of *E. lathyris* reported by different authors, which made it impossible to project with confidence the land area that would be required to generate latex equivalent to a barrel of gasoline [77] did not help the cause. By-and-by the prospect of 'extracting petrol in our own backyard' receded from public memory. Then, for a short while, the Indians were given the dream of 'herbal petrol' by a self proclaimed intuitive scientist, Ramar Pillai. He turned out to be a hoax and has been under investigation by India's Central Bureau of Investigation for possible involvement in large-scale frauds [78].

Currently jatropha is one of the hydrocarbon rich trees which is being given serious trial in India but without any *large-scale* or *widespread* use up to now. Out of the 7 species of jatropha (*Jatropha curcas*, *J. gossipifolia*, *J. glandulifera*, *J. tanjorensis*, *J. multifida*, *J. podagrica*, and *J. integirrima*), *J. curcas* is considered to be the most versatile. A great deal of material continues to be generated on the *promise* of hydrocarbon–rich plants but no single commercial application has emerged as yet. Indeed, observes Kalita [13] in the context of India – which is one of the countries where a great deal of governmental patronage has been extended to jatropha cultivation – 'we have not reached the stage of producing hydrocarbon plants on a large scale and the conversion process is yet to be standardized'.

As is the case with other biomass-based schemes for energy production, the initial calculations on jatropha look attractive. It has been estimated that upto 13 million hectares of land in India is available – including 3 million hectares of forest land and similar sizes of agricultural, fallow, and waste lands – for jatropha. The possible multi-faceted use of jatropha has been recounted. For example its litter enriches the underlying soil, it is useful as a medicinal and pest-repelling plant, and has other uses besides providing fuel oil. But, as in every other activity, the real picture would emerge only if we consider the indirect costs and hitherto unforeseen perils associated with widespread and large-scale implementation of the oil-from-jatropha programme. In a balanced overview, Ghosh et al. [79] have noted that not all of the wasteland is suitable to cultivate jatropha and that the plant is demanding in terms of nutrient requirement – especially nitrogen – if attractive yields are to be realized. While highlighting the virtues of jatropha biodiesel and the multifaceted utility of the other parts of the plant, the authors have also emphasized that the overall environmental impact of large-scale jatropha cultivation has not been studied so far. They have advocated careful assessment of the long-term impact of toxicity of the plant and its products.

7.1.2. Aquatic weed farms

Fast-growing aquatic weeds such as water hyacinth (*Eichhornia crassipes*), salvinia (*Salvinia molesta*) and duckweed (*Lemna minor*) can attain very high productivities, especially when cultivated on nutrient-rich wastewaters such as domestic sewage [80–84]. The weeds, on anaerobic digestion, yield about 300 l of biogas per kg of dried (105 °C) plant with a biogas of calorific value ~600 BTU ft^{-3} [80,85]. Innovative techniques developed recently by Sankar Ganesh et al. [47,86] enable generation of upto 2 m^3 of biogas per m^3 of reactor volume. It also appears possible to convert the 'spent' phytomass ensuing from the digesters to compost/vermicompost [16,22]. But whereas these appear good pathways to utilize weeds and other waste phytomass present in MSW, thereby facilitating their gainful disposal, as also capturing methane which is otherwise released to the atmosphere by the rotting of the phytomass in the open (thereby contributing to global warming), use of these processes to generate energy on a large scale is another matter altogether. It would require as much as 8 million hectares (180,000 square miles) of primary-treated sewage pond surface to generate 1 quad of gross energy. The sewage from a city of population 5 million can supply sufficient nutrients to support a 260 km^2 water hyacinth pond but cities of such size are not located near such large areas of free low-cost land. Further, the engineering implications of constructing, operating, and managing such gigantic sewage ponds can be staggering. It would be difficult to prevent percolation of sewage from such large ponds to the underground aquifers and the dangers of groundwater contamination would be very real. There would be other problems to contend with such as mosquito menace and propagation of pathogens. The ponds may also release methane and nitrous oxide from their anoxic zones, contributing massively to global warming because CH_4 and N_2O have 25 and 300 times stronger global warming potential than CO_2 [87,88]. Already 'constructed wetlands' which are used extensively throughout the world for treating biodegradable wastewaters, have come under scrutiny for their substantial contribution to GHG emissions in the form of CH_4 and N_2O [89].

7.1.3. Kelp farms

The marine giant brown kelp (*Microcystes pyrifera*) can attain productivities comparable to fast-growing sweet-water weeds such as water hyacinth [90–92]. It can be anaerobically digested to produced energy in the form of methane [93]. The ocean biomass farm systems have been conceived around the culture of algae such as *M. pyrifera* by employing artificial upwelling techniques. The original plan developed by Wilcox [94] called for the culture of kelp *sporophylls* in an aquarium. The cultures would then be attached to plastic lines and divers would attach these lines to a large floating grid of pipes. The pipes would distribute nutrient-rich water, pumped (with wave-power) from 300-m (1000 ft) depths. Harvest ships would be quite similar to those already used by the Kelco Company of San Diego to gather 'wild' kelp: these ships back through the kelp bed and underwater clippers cut the fronds to a depth of 1.2 m (4 ft), while a system of rakes and belts hauls the cut fronds into the ships' holds. Each of the three ships now in operation has a 400–500 tonne capacity. The project attracted wide interest and large funds especially in the USA.

Three test farms were installed [94]. The operations did not include artificial upwelling of deep-ocean water. The first farm, 7 acres in size, was placed in open ocean conditions about a kilometer off the north-eastern tip of San Clemente Island, California, in 100 m (300 ft) of water. About a 100 *M. pyrifera* plants were taken from nearby natural beds and attached to the farm which was suspended approximately 10 m below the ocean surface. The plan was to observe this farm for over 2 years. However, after 1 year, an anchor at one corner of the submerged grid came loose and the farm floated to the surface. A passing ship presumably tore the farm to pieces the next day, although the destruction might have been due to wave action [95].

Subsequent efforts centered around the Quarter-Acre Module (QAM), a concept of wire and rope lattice. The lattice would be

suspended from a buoy, on which the plants would be attached and which would use diesel pumps to bring up water from a depth of 1500 ft [96]. A number of problems emerged when the concept was first put to practice. The OTA [95], reports: 'It was not certain that sufficient nutrients would be provided by the artificial upwelling to stimulate kelp growth. In any event, there was no way to monitor the actual exposure of an individual plant to the pumped water. Then, when the pumps shut down, there was a reverse flow which damaged plants by sucking them into the ports. Finally, in January 1979, a severe storm carried away essential parts of the system, which, in turn, caused the plants to become cut and tangled. All of the original 100 kelp plants were destroyed'.

As the oil crisis began to ease in the 1980s, attempts were not made to try the QAM further. In recent years a case is again being made for marine biomas culture. For example Chynoweth [93] points out that 'the available ocean area and coastline area provide under utilized resources for marine farming', and that 'all of the U.S. energy needs could be supplied by marine microalgae grown on about 260 million hectares (one million square miles) of ocean'. Studies summarized by the same author [97] suggest that upwelling as a source of supply of nutrients for the marine biomass culture is too costly and that major technical challenge remains to successfully grow microalgae in the open ocean. However, assuming that such technical problems can be solved, kelp farms would still require major construction efforts, far larger than any previous marine engineering project. The GHG emissions that would result from the activities relating to the construction and operation of such a project would be staggering. Whether such a project will be able to yield carbon-neutral energy, that too without causing major disturbance in the already stressed ocean ecosystem, is hard to imagine.

7.1.4. Short rotation coppice willow/poplar, tall woody grasses such as miscanthus, switchgrass, and canary reed grass

High density plantations of upto 15,000 stools ha^{-1} have been proposed for willow/poplar [98] and around 20,000 plants ha^{-1} for grasses (Anon, 2004). Particular attention has been received by switchgrass (*Panicum virgatum*) as a 'model energy crop' due to its high biomass yields, broad geographic range, efficient nutrient utilization, low erosion potential, carbon sequestration capability, and reduced fossil fuel input requirements relative to annual crops [31].

7.1.5. Wheat, oilseed and fats

Wheat grain can be fermented and distilled to produce ethanol (as a fuel additive to petrol) as described earlier. Oilseed and fats can be used to make biodiesel by one of the three processes: by converting oil to its fatty acids and then to biodiesel, by acid-catalysed transesterification of oil, or by base-catalysed transesterification of oil. The latter process is the most common because it occurs at low temperature and pressure, requires no specialized expensive construction, allows direct conversion, and gives high yields with minimal reaction time or side reactions [99–101].

7.1.6. Corn and sugarcane

Of all the potential biomass-based energy sources, corn and sugarcane have been given the largest-scale and longest trial thus far. Both are fermented into ethanol which can either be used as additive of petrol (in cars basically designed for petrol) or as a stand-alone fuel (for cars specially designed to run on ethanol). The USA produced 4.86 billion gallons of ethanol from corn in 2006 and Brazil produced 3.96 billion gallons of ethanol from cane in 2005.

The process, detailed earlier, gives off large amounts of high-COD wastewater [46], besides carbon dioxide. The wastewater has BOD of the order of 18,000–37,000 mg L^{-1}, requiring about 4 kcal of energy per kg of BOD treated [102]. Most ethanol plants burn natural gas or, increasingly, coal to create the steam that drives the distillations, adding fossil-fuel emissions to the carbon dioxide emitted by the yeast [102,103]. Growing the fuel crops also requires nitrogen fertilizer, made with natural gas, and heavy use of diesel-fuelled farm machinery. Several LCA studies of the energy balance—the amount of fossil energy needed to make ethanol versus the energy it produces—suggest that the process ends up using more greenhouse gas emitting fossil fuel than it displaces [103–107]. Even if the energy balance is positive, it is not positive by large-enough magnitude to offset the adverse environmental impacts. Nor is it, by any stretch of imagination, significant enough to justify commitment of so much natural resources to produce fuel instead of the much bigger necessity, viz. food.

7.2. The environmental impacts

From the discussions in Sections 7.1.2 and 7.1.3, it is clear that only land-based biomass energy projects deserve serious consideration. Presently the focus indeed is on land-based projects. The following environmental impacts of large, land-based biomass energy projects can be discerned.

7.2.1. Biomass energy may be 'carbon neutral' but it is not 'nutrient neutral'

Central to the advocacy of biomass energy is the argument that it is 'carbon neutral'; it releases only that carbon back to the atmosphere which was earlier plucked out form the atmosphere in the act of photosynthesis. The argument is valid, too, even if we consider the fact that atleast a part of the carbon fixed by the biomass in recent years might have been of fossil fuel origin.

But biomass is not merely a lump of carbon, it contains nitrogen and several other essential nutrients. Any effort to intensively cultivate biomass has implications other than carbon capture; horticulture's contribution to the global nitrogen cycles is associated with many deleterious environmental consequences [108]. Presently agricultural activities generate >75% of emitted reactive nitrogen compounds [109]. Global atmospheric CO_2 concentrations have increased by about one-third since 1750; during the same period, a 15% increase in atmospheric N_2O concentrations has occurred. This figure begins assuming scary proportions if one realizes that each molecule of N_2O has 300 times greater global warming potential than a molecule of CO_2 [110,111]. Moreover, anthropogenic disruptions in the nitrogen cycle have led to an estimated 1100% increase in the flux of nonreactive atmospheric nitrogen to reactive nitrogen compounds [110]. Once converted to a reactive state, nitrogen persists in the environment, passing through the forms of NH_3, N_2O, NO_x, and NO_3; resulting in impacts such as the production of ground-level ozone, acidification, eutrophication, hypoxia, stratospheric ozone depletion, and climate change [112]. Of these impacts eutrophication of surface water bodies and contamination of underground aquifers are among the most widespread of the environmental impacts of agriculture. Phosphorous cycles are also effected leading to eutrophication.

It is not possible to sustain the intensive and repetitive production of biomass per unit land area envisaged in the biomass-based energy production programmes on the basis of the native nitrogen stocks in the soil as they are insufficient to supply enough nutrients to sustain non-nitrogen-fixing crops, such as corn. The natural levels of nitrogen have to be augmented with additional nutrients—generally in the form of synthetic fertilizer, although animal manures are also used (the latter have their own hazard of emitting methane which, molecule to molecule, has 25 times greater GW potential than CO_2). Synthetic fertilizers are made through energy-intensive processes; production of synthetic fertilizers is estimated to be responsible for 1% of global primary

energy consumption [113]. According to the National Academy of Sciences, Washington [114] corn production uses more nitrogen than any other crop produced in the USA.

Moreover soil organic matter, soil biota, water-holding capacity of the soil, and numerous microneutrients can not be replaced with fertilizers [115]. But even life-cycle assessments tend to neglect all these aspects while calculating energy input to fuel output ratios of biofuel production options [101].

7.2.2. Land and water resources

Implementing a substantial biomass energy production program requires large amounts of water resources and land. Horticulture is a massive water consuming activity; hectare for hectare, it requires more water by several orders of magnitude than is needed for domestic and industrial needs [116,117]. In some parts of western U.S. irrigated corn acreage, for instance in some regions of Arizona, groundwater is being pumped 10 times faster than the natural recharge potential of the aquifers [118]. It also contributes significantly to water pollution via the pesticides and fertilizers that are inevitably needed in sustaining any intensive cultivation [117,119]. The land used for increased biomass production for energy competes with crops, forests, and urbanization [117,120]. This competition can be illustrated by comparing the crop land needed to feed one person with that required to fuel one automobile for one year. If we assume that the average automobile travels 16,000 km per year and gets 15 km/l, then 1200 l of gasoline will be required per year for an automobile. Using straight ethanol, the total in equivalent kcal would be 2000 l. Assuming a zero energy charge (no high grade fuel used) for the fermentation/distillation processes, then 2.2 ha of land would be required to provide this much fuel. In comparison, about 0.5 ha of cropland is used to feed each person. Thus four times more land is needed to fuel an automobile than to feed one person. Further, the demand for agricultural and forest products is growing rapidly with time, enhancing the already wide gap between demand and supply, thus increasing ever more the competition for land and water resources. In India biofuel extracted from jatropha is yet to make any impact whatsoever on the country's fossil fuel bill, yet jatropha cultivation has already impacted food prices in some regions as farmers have shifted from food crops to jatropha cultivation [121].

Converting rainforests, peatlands, savannas, or grasslands to produce food-based biofuels in Brazil, Southeast Asia, and the United States has created a 'biofuel carbon debt' by releasing 17–420 times more CO_2 than the annual greenhouse gas (GHG) reductions these biofuels provide by displacing fossil fuels [107].

Accelerating demand for palm oil is contributing to the 1.5% annual rate of deforestation of tropical rainforests in Malaysia and Indonesia [122]. An estimated 27% of concessions for new palm oil plantations are on peatland tropical rainforests, totaling 2.8×10^6 ha in Indonesia. Brazilian Cerrado is being converted to sugarcane and soybeans, and the Brazilian Amazon is being converted to soybeans [123,124]. Grassland in the US, primarily rangeland or land currently retired in conservation programs, is being converted to corn production. Rising prices for corn, wheat, and soybeans could cause a substantial portion of the 1.5×10^7 ha of land currently in the US Conservation Reserve Program to be converted to cropland [125]. According to Fargione et al. [107] the net effect of this land-use change is to increase CO_2 emissions for decades or centuries relative to fossil fuel use!

The removal of biomass from land and water for energy production programme increases soil and water degradation, flooding, and removal of nutrients. It also affects wildlife and the natural biota. These and other threats to the environment from the production of biomass are not seen by many whose attention is riveted on the perceived 'carbon neutral' nature of biomass energy.

7.2.3. Soil erosion and water run-off

Biomass energy production projects are likely to exacerbate soil erosion problems. Although the use of available technologies can minimize erosion, they are difficult and costly to implement. In developing countries like India and Brazil they may not be implemented at all [126–129]. Producing energy crops such as corn for ethanol requires additional agricultural land. To do this, marginal cropland that is highly susceptible to soil erosion would have to be brought under corn cultivation. Soil erosion contributes significantly in hastening water run-off, thus, retarding groundwater recharge; the nutrient-rich run-off can harm the quality of receiving rivers, lakes or estuaries by causing eutrophication [130].

Moreover, as has happened with eucalyptus in developing countries like India, the temptation to make quick profit from a product with high current demand, prompts the farmers to substitute food crops with trees like eucalyptus, and harvest them more often than is sustainable, harming the environment as well as their own long-term prospects [129,131,132]. Wherever possible, natural forests and croplands are encroached upon for the plantation of 'cash' crops; with disastrous results.

7.2.4. Nutrient removal and losses

Significant nutrient loss is incurred by the harvesting of crop residues for biomass energy. With the corn yield of 7840 kg/ha, the nutrients contained in both grain and residues are 224 kg N, 37 kg P, 140 kg K, and 6 kg Ca [133], nearly half of the nutrients are in the residues. The amount of energy needed to replace the nutrients lost when the biofuel plants are harvested would be the equivalent of at least 460 l of oil per hectare (Pimental et al., 1994a,b).

7.2.5. Loss of natural biota, habitats and wildlife

Conversion of natural ecosystems into energy-crop plantations will change both the habitat and food sources of wildlife and other biota [128–130]. Alteration of forests and wetlands will reduce many preferred habitats and mating areas of some mammals, birds, and other biota [134,135].

Monoculture plantations of fast-growing trees reduce the diversity of vegetation and the value of the areas as habitats for many wildlife species. These monocultures are less stable than climate forests and require increased energy inputs in the form of pesticides and fertilizers to maintain productivity. Trees in profitable plantations are 2–3 times as dense as those of natural forests [135]; the high stand density may result in greater pest problems [127].

7.2.6. Social and economic impacts

The major social impacts will be shifts in employment and increases in occupational health and safety problems. Total employment overall is expected to increase if the nation's energy needs are provided by biomass resources [136]. The labour force would be needed in agricultural and forest production to cut, harvest, and transport biomass resources and in the operation of conversion facilities.

The direct labour inputs for wood biomass resources are 2–3 times greater per million kcal than coal [133]. A wood-fired steam plant requires, 4 times more construction workers and 3–7 times more plant maintenance and operation workers than a coal-fired plant. Including the labour required to produce corn, about 18 times more labour is required to produce a million kcal of ethanol than an equivalent amount of gasoline [137].

Associated with the possibilities of increased employment are greater occupational hazards [138,139]. Significantly, more occupational injuries and illnesses are associated with biomass production in agriculture and forestry than with either coal (underground mining), oil, or gas recovery operations [140–143]. Agriculture reports 25% more injuries per man-day than all other private industries.

7.3. The real societal cost of grain-based biofuels

The energy inherent in grain is much better utilized for human benefit when the grain is directly consumed as food instead of its use as a biofuel feedstock. Utilization as food also enables driving maximum benefit from the nutrients present in the grain. Hence use of corn and other grains to generate biofuel amounts to a substantial depreciation of the grain's value as the most basic, life-sustaining, energy source. This translates, in the ultimate analysis, into wastage of, rather than generation of, clean energy.

With the global reserve food stocks having reached their second lowest levels in history [144]; with the demand – hence the price – of food rising almost everywhere; and with thousands of additional people sliding into the zone of the perpetually hungry by the minute, it appears strange logic to convert food into fuel on the belief that such an endeavor will benefit mankind and reduce GHG emissions!

How biofuel programmes can harm the interests of food-starved people can be illustrated by this example: Currently 3 million tones of extra wheat produced by the UK is exported to the needy countries but it is now being suggested to reduce that much wheat production and use the freed land for biofuel crops [145]. In poorer countries like Brazil where a large number of undernourished human beings live, using land to produce biofuel instead of food is particularly saddening.

7.4. Conversion to utilizable energy

7.4.1. Impact of thermal processes

Production of biomass is only one dimension of the biomass-based energy systems; its conversion to utilizable energy is another and equally important dimension. Several technologies are available for biomass conversion (Fig. 2); of these the most widely used are direct combustion and pyrolysis [67,146]. By now it is universally accepted that biomass utilization in this manner is a source of not only GHG emissions but several highly toxic air pollutants as well [36,119,147,148]. Yet it is not only continued to be used in this manner but is continued to be promoted as 'feasible' without any consideration for the environmental impact [146,149,150]. The government of India's Ministry of New and Renewable Energy (MNRE) in fact provides financial incentives to private entrepreneurs for installing thermal and thermochemical conversion based biomass energy plants [7]; it is possible that governments elsewhere may be similarly subsidizing this form of biomass energy generation as well. Interestingly, and in tune with the widely prevalent (through unsubstantiated) belief that all forms of renewable energy production are a boon to the environment, MNRE calls the biomass gasification process 'relatively clean and acceptable in environmental terms' [7]. To get the energy needed for the production of 'clean' ethanol, huge quantities of bagasse are used as fuel in Brazil contributing substantially to GHG emissions. Even the optimists among the proponents of renewable energy sources (for example [151,152]) acknowledge the serious environmental pollution hazards associated with biomass utilization as an energy source.

Broadly the impacts of thermal conversion technologies are:

(a) air pollution—emissions of particulates, carbon oxides, sulphur oxides, nitrogen oxides;
(b) organic emissions—dioxin, hydrocarbons, toxic irritants such as acid, aldehyde, phenol, and carcinogenic compounds such as benzopyrene;
(c) generation of solid wastes—bottom ash, flyash sometimes containing toxic substances with accompanying pollution problems;
(d) water pollution—biological oxygen demand, chemical oxygen demand, suspended solids, trace metals;
(e) pressure on land and water resources;
(f) household hazards—accidental fires;
(g) occupational hazards—prolonged exposure to toxic and corrosive chemicals.

All in all the problems of air pollution associated with conversion of lignous biomass to energy are no less significant than the ones we are familiar *vis a vis* conversion of coal and oil [2,131]. These are significant even at the very small scale of residential wood-burning. The smoke has harmful levels of carcinogens and other toxicants. Lastly in terms of a million kcal output, forest biomass has several times more occupational injuries and illnesses than coal and oil mining [143].

7.4.2. Impact of fermentation processes

Brazil has the biggest 'fuel from biomass' programme in the world based on fermentation process. It employed sugarcane grown over millions of hectares and produced by its fermentation 3.96 billion gallons of ethanol in 2005 [103]. No comprehensive environmental impact assessment of this activity has been done so far but the situation is reflected in this comment by Gaulart (quoted in [103]): "if alcohol is a 'clean' fuel the process of making it is very dirty". To drive away snakes which inhabit large sugarcane plantations and to make the cane easier to remove manually, the fields are usually burned before the harvest causing severe air pollution besides releasing greenhouse gases into the atmosphere. Moreover natural forests are being increasingly cleared (often by burning the foliage after removing timber) to make way for sugar plantations. These activities contribute a lot more to global warming, over a shot term as well as a long term, than the savings achieved by replacing some portions of gasoline by ethanol in transportation fuel [106,107].

The US plans to divert a third of its maize crop to biofuel production in 2009. UK, Germany, Spain, and France also plan to go for biofuel production [135,154]. In an independent assessment Kohl and Ghazoul [155] have identified numerous likely negative impacts of EU's biofuel programmes and have advocated the need for comprehensive assessment of their environmental impacts. Eventhough life cycle assessment studies continue to be reported which show biofuels in favourable net energy balance (NEB) in comparison to the fossil fuels they replace [69,101], biofuels look less and less attractive if viewed in the total context of energy balance, GHG emissions, environmental impact, and humanism. There is increasing advocacy for bio-fuel production from lignocelluloses-based energy crops such as switchgrass, willows, and poplars [68,69], especially using agriculturally marginal land to reduce competition from food production. Several assessments, which leave out some or other aspects of the 'cradle-to-the-grave' journey of lignocelluloses-based energy crops [66,68,69,156,157] show them in more favourable light than corn or sugarcane *vis* a *vis* net reduction in GHG emissions, but full-fledged energy balance and environmental impact assessment studies of these options have not yet begin to come out in profusion. According to Pimental and Patzek [102] converting switchgras into ethanol results in a negative energy return which is 50% or slightly higher than the negative energy return for corn ethanol production. The two major

energy inputs for switchgrass conversion into ethanol are steam and electricity production.

7.5. Is there hope?

Biomass *can* become a great source of truly carbon-neutral energy on a large-scale if processes can be developed to *economically* and *cleanly* convert highly ligneous stems and branches of sugarcane, corn, woody grasses, etc.—which can currently be used as energy source only via thermal or thermochemical conversion—into ethanol-like liquid fuel. Intensive R&D is going on [158–162] but there is no success in sight as yet. Likewise biofuel production from algae is also a great prospect [58,63,64] but, sadly as of now, only a prospect!

8. Biomass energy—dispersed systems

Dispersed biomass energy utilization systems can be of two types:

(a) household systems using biomass directly as a fuel;
(b) community sized electricity/heat producing systems based on pyrolysis, gasification or liquifaction.

The first type of dispersed systems is widely used in developing countries, including India [163,164]. It has been estimated that nearly 70% of India's cooking energy requirement, and about 32% of all primary energy requirements, are still met with biomass [7]. Even more startling are the findings that as much as one-fourth of the household income in Indian villages may be coming from biomass extracted from common lands. Though crop wastes form a part of this supply, the bulk of the supply comes from firewood. Extraction of wood from forests to meet this requirement is one of the major factors responsible for the loss of forests in developing countries. It has been estimated that, in India alone, the current annual withdrawal of fuelwood from forests is of the order of 220 million tonnes whereas the sustainable production capacity is only about 28 million tonnes. There are no quantitative studies on the impact that firewood extraction of this magnitude exerts on the underground water and soil productivity but considering the size of the extraction, the extent of the adverse impact is not difficult to imagine. Fuelwood can be sustainably derived from any unit of land only if the rate of regrowth equals or exceeds the rate of extraction. But such favourable dynamics are not possible if the essential energy needs of a populous country like India are to be met, more so when fuelwood has to compete with agriculture for the limited land available.

The use of fuelwood directly in homes is a very serious source of air pollution, and a major health-hazard for women and children who are exposed to this pollution for significant lengths of time [165]. A great deal of effort has gone in designing 'smokeless' *chulhas* (burners) or *chulhas* with better fuel efficiency [166] but a very large number of rural households still use the conventional mud-cast chulhas. High levels of air pollution builds up in dwellings which use biomass due to essentially poor cross-ventilation in such dwellings. It has been reported [2,153,167,168], that the emissions of air pollutants such as carbon monoxide, sulphur dioxide, nitrogen oxides, organics, and particulates are much larger—compared to other sources—from the burning of biomass [148]. The emissions include carcinogens and teratogens [147,148].

As for community sized biomass-based energy sources the pollution problems are similar to large installations such as thermal power plants. But, whereas in the latter, the centralized nature of the problem and the economics of scale makes it possible to treat the air pollutants significantly before release of the flue gases, little or no treatment is possible, or done, at smaller scales and none whatsoever at the household level. Dispersed use of biomass is, in fact, more harmful than centralized use for this reason. A large number of small backyard, neighborhood, or even community-sized coal gasification or liquifaction plants would not only be less economical but ecologically more harmful than a centralized facility with *the same total output* of synfuel. At lesser scales it will be very difficult to achieve as stringent a level of air and water treatment as is possible in the centralized systems. And even if the dispersed plants dispose off the same total quantity of pollutants into the environment as the centralized plants, it is likely that a greater reach of the habitat would be effected by the former.

Moreover, the damage is not likely to be significantly more diluted by dispersal than by centralization; in dispersed use the quantity of waste generated at a site is small but then the preparedness to handle the waste is either very little or not at all. Whereas centralised systems are subjected to surveillance by regulatory agencies and can afford to take pollution control measures, such regulation is not possible in dispersed use. These considerations may appear speculative, but are not far fetched if we take into account the seriousness of air pollution problems already noticed during dispersed biomass utilization. Even in a developed country such as UK, pollution generated per unit of electricity produced by small-scale biomass-based systems is much higher than by larger scale systems mainly due to greater affordability of stricter pollution control in the latter [37]. It is also well-known that small-sized neighborhoods and small-scale industries are able to get away more easily despite disposing untreated wastes on nearby lands due to the difficulty in policing them [119].

9. Summary and conclusion

When seen from the limited perspective of standing crop, theoretical replenishabitity, and 'carbon neutral' character as a fuel, biomass appears to be a very attractive source of renewable energy. Biomass energy is indeed a sustainable option, and has proved to be so for thousands of years, but only as long as it is used to a very limited extent. The picture begins to change once the likely impacts of biomass energy generation and utilization on the large scale presently envisaged are considered.

The paper estimates the different forms of biomass that are theoretically utilizable as source of energy and catalogues the technological routes presently available to effect the utilization. It then examines in detail the environmental impacts of large-scale generation and utilization of biomass through different routes.

It is brought out that even as biomass may be 'carbon neutral', it isn't 'nutrient neutral'; cultivation of all species independent of their productivity exert varying extents of pressure on the nutrients contained in the soil on which the cultivation is done. Moreover, the quantity of fossil fuel saved in the course of the production and the utilization of biofuels is not always greater than the quantity of fossil fuels used. These factors, besides the environmental degradation and ecological disruptions caused in the course of large-scale biomass cultivation, put serious question marks on the sustainability of the existing biomass-to-energy programmes.

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